HYDRAULIC CHARACTERIZATION OF GEOHYDROLOGIC COLUMNS

ABSTRACT

geohydrologic column at an aquifer-storage-and-recovery site is critical for assessing performance. A methodology was developed for characterizing geohydrologic columns that extended greater than 2,000 ft below land been located and installed within the Southwest Florida Water Management ,000 ft. Aquifers were pumped individually and water levels event. Drawdown estimates at a site were interpreted with a single numerical model that extended from land surface to the base of the geohydrologic column and simulated all pumping events. Hydraulic conductivity was assumed to be homogeneous and isotropic within each aquifer and confining unit. Hydraulic-property estimates for all of the aquifers and confining units were consistent and reasonable because results from multiple aquifers and pumping events were analyzed as a

INTRODUCTION

Ground-water withdrawals in southwest Florida are expected to increase and existing water supplies are considered insufficient to meet the projected demand by the year 2020. The area depends primarily on ground-water pumped from three aguifer systems, the surficial aguifer system, the intermediate aguifer system, and the Floridan aquifer system. The ground-water resources are geographically limited by the quantity or quality of water in each aquifer system. Generally, ground-water resources are small to moderate in the surficial aquifer system, moderate in the intermediate aquifer system, and abundant in the Floridan aquifer system.

Developing alternative methods for augmenting water supplies is a major priority to water managers. Aguifer storage and recovery (ASR) is a method in which surplus water can be injected into the subsurface during wet months through injection wells and later recovered from those same wells during dry months. Field-scale estimates of aquifer and confining unit hydraulic properties are needed to effectively assess the potential for ASR.

In 1975, the Southwest Florida Water Management District (SWFWMD) implemented a Regional Observation and Monitor-well Program (ROMP) to increase their knowledge of the hydrogeologic system in west-central Florida One of the objectives of this Program was to assess the hydraulic properties of aquifers and confining units. The present network consists of many inland and coastal monitoring sites with 2 to 4 wells per site (Figure

Multiple aguifer tests have been conducted at many of the ROMP sites). However, careful, controlled, and successful aquifer tests are difficult to conduct in west-central Florida because aguifer systems have a layered and non-uniform permeability distribution. Heterogeneous fractured rock, the occurrence of multiple aquifers, and partially penetrating wells cause unknown deviations from analytical solutions. Unknown errors in hydraulic property estimates are introduced by many deviations from the inherent assumptions in analytical solutions.

Numerical simulation of aquifer-test data provides an alternative method of determining hydraulic properties and allows for consistent comparisons of models with different representations of heterogeneity. The numerical simulations and results are considered more realistic for heterogeneous aquifer systems and complex ground-water flow, in contrast to analytical methods that have inherent limitations for deriving solutions applied to simple hydrogeologic conditions.

Purpose and Scope

This report documents an approach for field scale estimation of the hydraulic properties of a geohydrologic column. Techniques for defining geohydrology, well construction, pumping history, drawdowns, and initial estimates of hydraulic conductivity are described so that multiple aguifer tests can be interpreted with a single numerical model. Spreadsheet based software that facilitates the implementation of the geohydrologic column approach is described. Pragmatic guides for using drawdowns from pumping wells, weighting negligible drawdowns, and initializing parameter estimates also are presented.

Approach

Consistent hydraulic properties for a geohydrologic column are estimated from multiple aquifer tests with a single MODFLOW model. This approach will be referred to as the geohydrologic column approach in this report. While the geohydrologic column approach is very flexible, a few assumptions are adopte Aquifers and confining units are assumed to be flat-lying and laterally isotropic, which allows radial symmetry to shift between production wells as each test is analyzed. The number of aquifers in a geohydrologic column is limited to the number of stressed intervals. These assumptions primarily are imposed by data limitations, not MODFLOW.

Well location and construction are needed for all wells (Table 1). Locations of wells are defined in Cartesian coordinates such as Universal Transverse Mercator (UTM). Cartesian coordinates are used to compute radial distances between a production well and observation wells. Multiple radial distances exist for each observation well because distances differ to each production well.

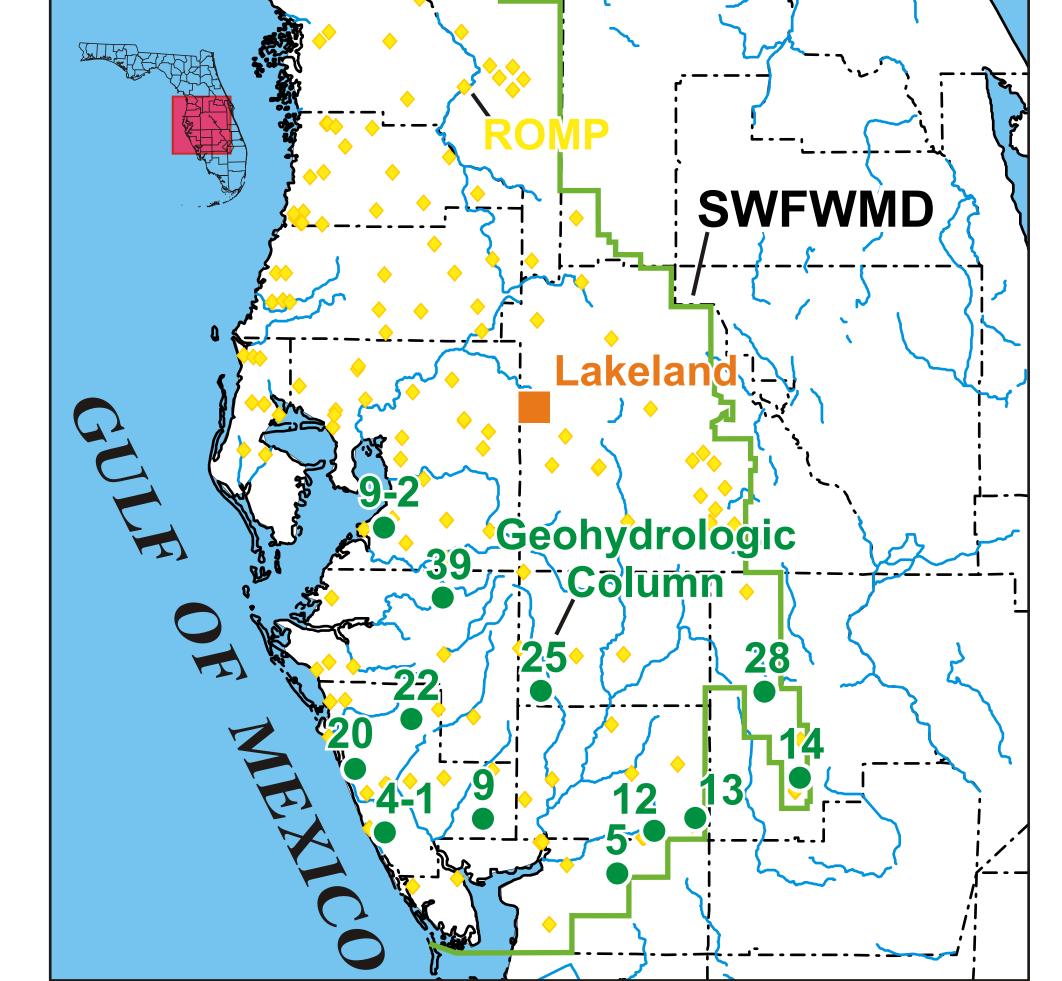


Figure 1.- Locations of ROMP and geohydrologic column analysis

Table 1.-Well location and construction information from ROMP 12.

SITE	Easting, Feet	Northing, Feet	Land Surface Feet	Top of Screen BLS Feet	Bottom of Screen BLS Feet	Well Diameter Inch
MW1	1,398,899	9.813.117	40	2	5	4
MW2	,	9,813,129	40	12	27	4
MW3	,	9,813,125	40	60	110	8
MW4	1,398,862	9,813,132	40	280	409	8
MW5	1,398,846	9,813,118	40	487	710	8
MW6	1,398,875	9,813,117	40	720	905	8
MW7	1,398,826	9,813,123	40	1100	1373	12
MW8_UPZ	1,398,837	9,812,974	40	55	110	2
MW8_MPZ	1,398,837	9,812,974	40	285	414	2
MW9	1,398,812	9,812,974	40	490	705	2
MW10_SUW	1,399,300	9,812,962	40	725	909	3
MW10_AvPk	1,399,300	9,812,962	40	1085	1405	6
MW11	1,398,942	9,812,962	40	8	15	2
MW12	1,398,908	9,813,064	40	13	28	4

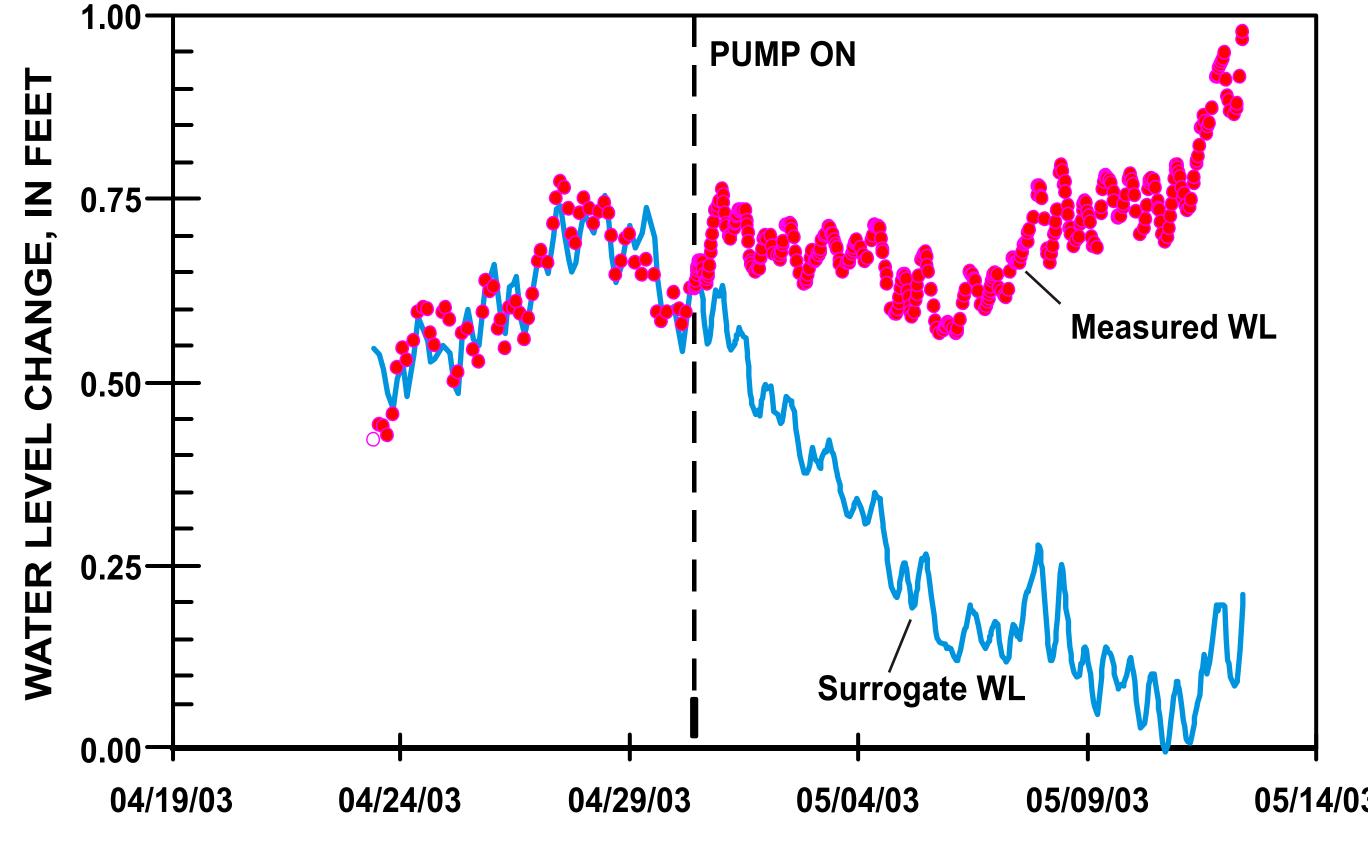


Figure 2.- Small drawdowns superimposed on noisy water-level measurements and a surrogate water-level approximation.

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Drawdown Interpretation

water level and what the water level would have been in the absence of pumping. Drawdowns conventionally are estimated by assuming the static water level prior to pumping is equivalent to unpumped water levels during a test. This approach is adequate when water level changes are large relative to environmental noise, but is deficient when drawdowns are equivalent or less than environmental noise (Figure 2). Small drawdowns frequently are observed in transmissive aguifers such as the Upper Floridan and in aguifers adjacent to pumped aquifers.

A hydraulic conductivity and likely error can be assigned to a confining u when small drawdowns in the confining unit or adjacent, unpumped aquifer are identified positively. Undetected drawdowns in monitored wells outside of the pumped aguifer only can be used to estimate the maximum hydraulic conductivity of a confining unit. Positive detection of small drawdowns is more likely when a reliable surrogate is available for what water levels would have been in the absence of pumping (Figures 2 and 3). Estimators of unpumped water levels will be referred to as surrogate water levels in this report

Surrogate water levels are the summation of multiple time series such as arth tides. water levels, barometric pressure, temperature, or any other ontinuous signal that is unaffected by pumping during an aquifer test. urrogate water levels in a well are fitted to measured water levels prior to umping by adjusting the amplitude and phase of each time series. A best fit obtained by minimizing the sum-of-squares difference between simulated nd measured water levels. Gross errors in estimated drawdown are inferred om the optimization error.

nitial Hydraulic Property Estimates

Initial hydraulic property estimates of the aguifers and confining units are eeded for a MODFLOW model of the geohydrologic column. Transmissivities the aguifers are estimated initially with the Cooper-Jacob method because ne solution is simple and can be solved graphically (Halford and Kuniansky, 002). Drawdown in the pumping well is analyzed because drawdowns are reatest and a transmissivity estimate is affected less by leakage. Aquifer orage and vertical hydraulic conductivity and specific storage of adjacent onfining units are estimated initially with a leaky aquifer solution which also ovides another estimate of transmissivity (Moench, 1985). The Cooper-Jacob estimate of transmissivity provides an upper bound on the leaky aquifer olution which is solved by optimization within a spreadsheet.

Geometric means of analytical estimates define initial hydraulic conductivity estimates of the aquifers and confining units in the MODFLOW model (. The geometric mean of the Cooper-Jacob and Leaky solutions is divided by aguifer thickness for an initial hydraulic conductivity estimate. An initial estimate of the hydraulic conductivity of a confining unit is the geometric mean of hydraulic conductivities from Leaky solutions above and below a confining unit. Specific storage is specified initially as 1.E-6 ft⁻¹ in all units because storage estimates from the analytical solutions tend to be unreliable.

Parameter estimation works better where initial hydraulic conductivity estimates are within 1 to 2 orders of magnitude of the best estimates because the general shape of measured drawdown time-series must be simulated initially. For example, the flattening of a drawdown curve is controlled by the hydraulic conductivity and specific storage of a confining unit (F Parameter estimation will not be sensitive to changes in hydraulic conduct and specific storage of a confining unit if initial estimates do not flatten the curve where measured drawdowns are present.

Numerical Model

Wells and aguifer flow system are simulated with an axisymmetric, radial geometry in a single MODFLOW layer. Radial distance increases with increasing column indices and depth increases with increasing row indices. Hydraulic conductivities and storages of the ith column are multiplied by 2 r_i to simulate radial flow where r was the distance from the outer edge of the first column to the center of the ith column (Figure 5)

Vertical discretization is coarse for aquifers and fine for confining units. Aguifers are defined with a primary row that simulates most of the thickness and two 0.01-ft thick rows above and below the primary row to simplify interpretation of hydraulic property estimates. Confining units are discretized 05/14/03 variably into 20 rows or more to adequately simulate drawdown diffusion between aquifers. Rows range in thickness from 1 to 10 percent of the total thickness of a confining unit with the thinnest rows being adjacent to the aguifer-confining unit contacts.

Multiple aquifer tests are simulated with a single model by using multiple stress periods. For example, drawdown during three aquifer tests from a geohydrologic column would be simulated in three stress periods. Elapsed time and off-site stresses between aguifer tests are not simulated. Effects of off-site stresses are assumed to be eliminated when drawdowns are estimated so heads are initialized to zero at the beginning of each stress period.

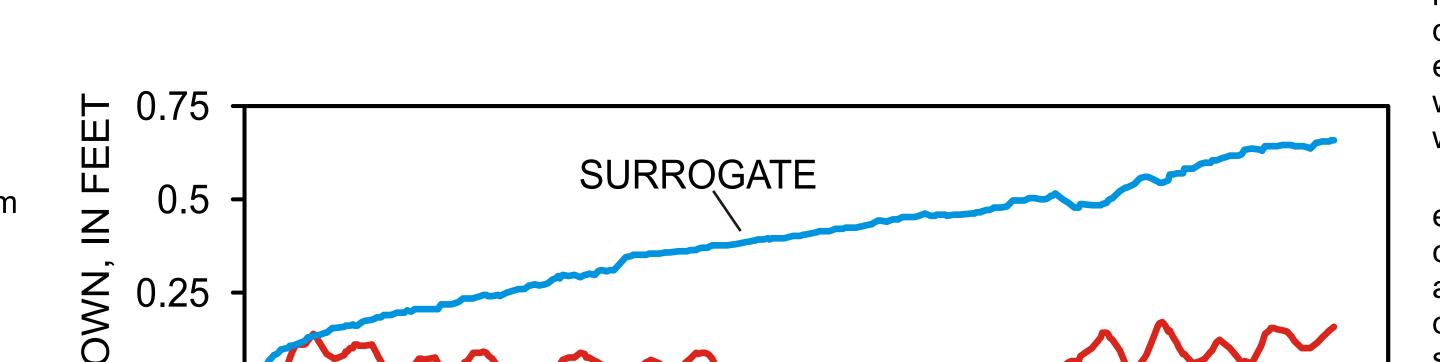
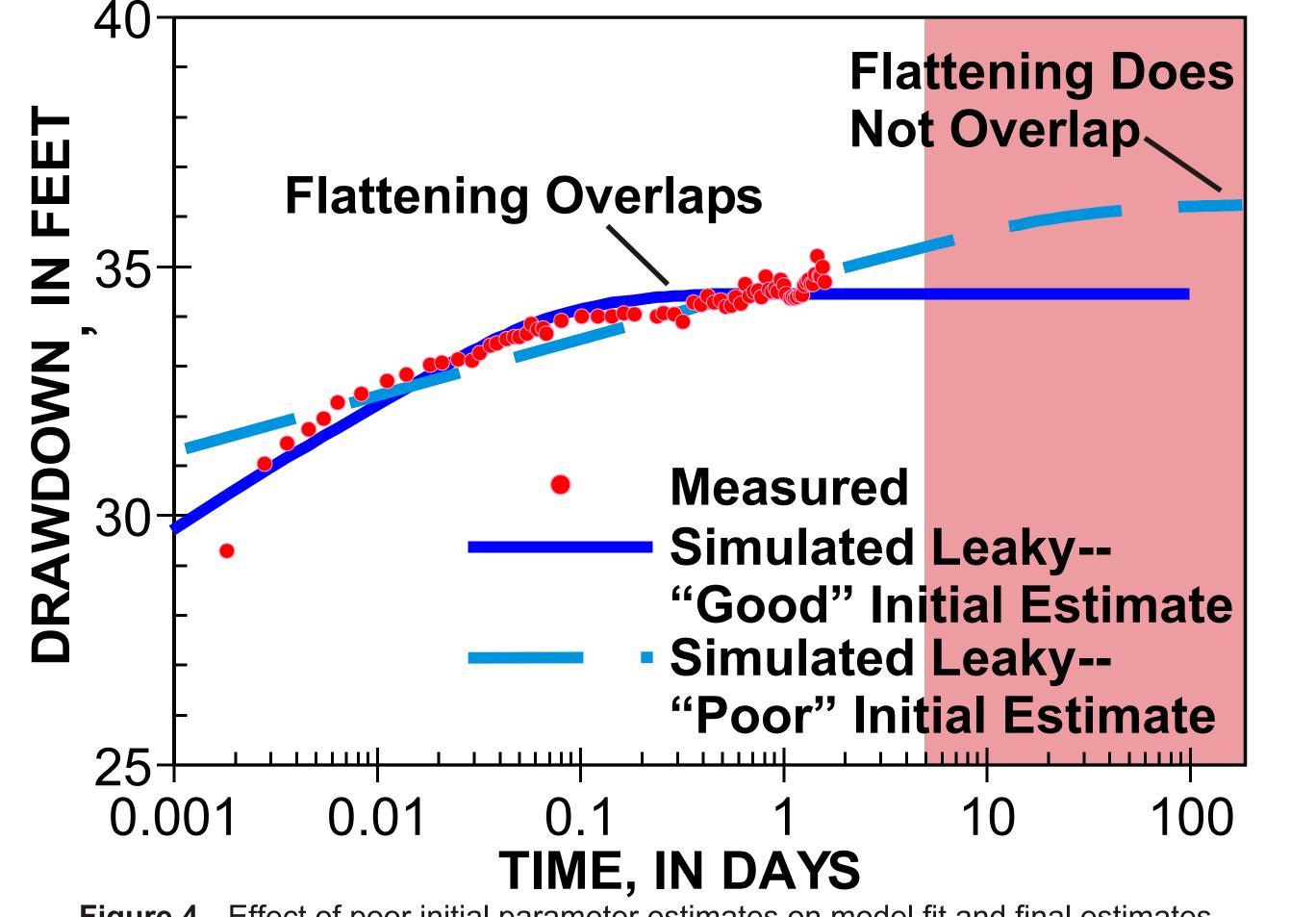


Figure 3.- Small drawdowns estimated by the conventional method and by the surrogate water level approach.

 Table 2.-Initial estimates of hydraulic properties from analytical solutions for ROMP

ELAPSED TIME, IN DAYS

UPZ 6,100 1,600 0.0007 0.23 4.E-07 3,10 MPZ 1,200 160 0.0007 0.70 5.E-07 44 LPZ 48,000 6,500 0.000005 0.62 3.E-03 18,00	CJ-Line CJ-Line			Lea	G	GEOMEAN		
UPZ 6,100 1,600 0.0007 0.23 4.E-07 3,10 MPZ 1,200 160 0.0007 0.70 5.E-07 44 LPZ 48,000 6,500 0.000005 0.62 3.E-03 18,00		AQUIFER	T, ft ² /d	T, ft ² /d	S, d'less	K', ft/d	S', 1/ft	T, ft ² /d
MPZ 1,200 160 0.0007 0.70 5.E-07 44 LPZ 48,000 6,500 0.000005 0.62 3.E-03 18,00	•	SAS	<u>390</u>					390
LPZ <u>48,000</u> <u>6,500</u> 0.000005 0.62 3.E-03 18,00		UPZ	<u>6,100</u>	<u>1,600</u>	0.0007	0.23	4.E-07	3,100
		MPZ	<u>1,200</u>	<u>160</u>	0.0007	0.70	5.E-07	440
S_{11} S_{12} S_{13} S_{14} S_{15} S		LPZ	<u>48,000</u>	<u>6,500</u>	0.000005	0.62	3.E-03	18,000
3uwannee 13,000 3,000 0.000002 0.30 2.E-04 7,40		Suwannee	<u>15,000</u>	<u>3,600</u>	0.000002	0.30	2.E-04	7,400
AvonPark 1,200,000 900,000 0.001 20.09 2.E-01 1,000,00	_	AvonPark	<u>1,200,000</u>	900,000	0.001	20.09	2.E-01	1,000,000



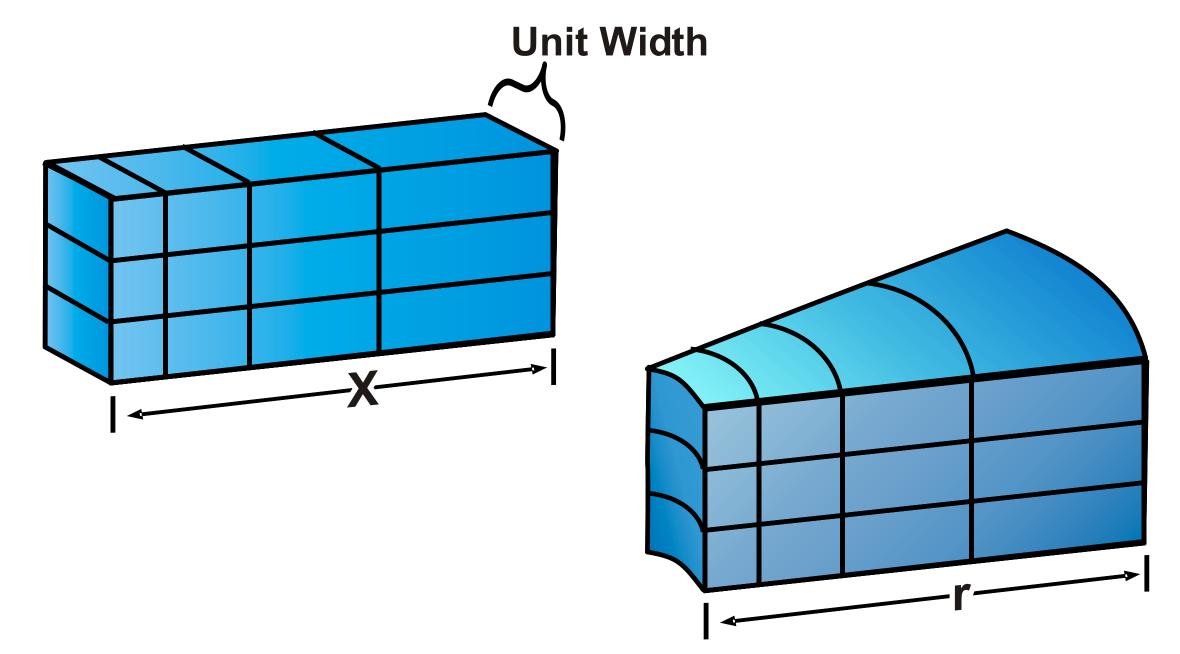


Figure 5.- Effect of multiplying hydraulic properties by 2 r on effective width of a

Parameter Estimation and Observations

well which are responses to pumping events above, in, and below the aquifer where a well is screened. Each drawdown time-series is written to a separate file that is named after the pumped aquifer and well. For example, the file OBSERVE ROMP12-AvonPark MW9.txt contains drawdowns in well MW9 from pumping in the Avon Park aguifer at the ROMP 12 site.

Application to ROMP 12

ROMP 12 is located at 27°02'25"N and 81°44'33"W in Desoto County near the iqure 7). Fourteen wells were completed at ROMP 12 and ranged from 2 to 12 inches in diameter (Table 1). The deepest well, MW10 AvPk, was drilled to more than 1.400 ft below land surface. Six aquifer tests were conducted at ROMP 12 between July 1997 and November 1998. Discharge was least from the surficial aquifer at 20 gallons per minute (gpm) and was greatest from the Avon Park at 5,200 gpm. More than 10 million gallons were discharged cumulatively from all six

The geologic framework that forms the aquifer systems underlying the ROMP 12 site consists of undifferentiated surficial deposits, heterogeneous marine deposits comprising the Hawthorn Group, and persistent carbonates comprising the Suwannee Limestone, Ocala Limestone, and Avon Park Formation. Stratigraphic and hydraulic units forming the hydrogeologic framework were delineated using lithologic and geophysical logs water levels, water quality, and hydraulic characteristics from the ROMP 12 test site.

The intermediate aguifer system and Upper Floridan aguifer system are the principa hydrogeologic units that underlie ROMP 12 (Figure 8). The intermediate aquifer system is composed of clastic sediments interbedded with carbonate rocks. Interbedded clay and finer grained clastics form the confining units that separate the carbonate rock aguifers. The Upper Floridan aguifer system is the lowermost aguifer system underlyi the ROMP 12 site and consists of a thick, stratified sequence of limestone and dolomite The Ocala Limestone is less permeable than the adjacent Suwannee Limestone and Avon Park and is a confining unit in the Upper Floridan Aguifer System. Chloride concentrations exceed 300 mg/l in the Suwannee Limestone and range from 450 to 18,000 mg/l in the Avon Park.

Thirty drawdown time-series were estimated from the six aguifer tests at ROMP 12

Drawdowns at the end of each aquifer test ranged from about 15 to 50 ft in the pumping wells and ranged from less than 0.2 ft to 5 ft in the observation wells. Drawdowns were attenuated greatly by confining units. For example, pumping 730 gpm from MW6 caused about 3 ft of drawdown 400 ft away in the Suwannee aguifer and less than 0.5 ft of drawdown less than 50 ft away in adjacent aguifers (Figure 9). Drawdown estimation with surrogate water levels was limited because antecedent conditions and background water levels were not monitored at ROMP 12.

Numerical Model of ROMP 12

confining units in the geohydrologic column of ROMP 12 (Figure 8) by fitting simulated drawdowns to measured drawdowns from six aguifer tests. Drawdowns were simulated with a two-dimensional, radial MODFLOW model (McDonald and Harbaugh 1988: Harbaugh and McDonald, 1996). Parameter estimation was performed by minimizing a weighted sum-of-squares objective function with MODOPTIM (Halford, in review). Hydraulic conductivity of the surficial aguifer was not estimated with the numerical model and was assigned a transmissivity of 400 ft²/d from a Cooper-Jacob analysis. The model extended from the production wells to 200,000 ft away and from water

table to 2.100 ft below land surface. The model domain was discretized into a laver of 116 rows of 69 columns (Figure 8). Cell widths ranged from 0.2 ft adjacent to the production well to 33,000 ft in the farthest column. Vertical discretization also was variable and finer across the confining units. All external boundaries were specified as no-flow. Changes in the wetted thickness of the aquifer were not simulated because the maximum drawdown near the water table was small relative to the total thickness.

The aguifer tests were simulated with five 10-day stress periods. Initial heads were set to 0 at the start of each stress period. Stress periods of 10 days were specified for convenience so drawdown observation time would be equivalent to elapsed time during each successive test plus a multiple of 10 d.

minimize the objective function. Lateral hydraulic conductivities of the five confining units and five aguifers other than the surficial aguifer comprised ten of the knobs. Specific storage of the same geohydrologic units comprised the nine remaining knobs. Specific storages of the two shallowest confining units were defined with a single knob because their lithologies were similar and were correlated highly as independent knobs. Vertical

Simulated and "measured" drawdowns were matched by twiddling 19 knobs to

aguifer tests with a RMS error of 0.3 ft. RMS errors of individual aguifer tests ranged from 0.1 ft for the UPZ, LPZ, and Suwannee tests (Figure 9) to 0.5 ft for the Avon Park test. Simulated drawdowns did not match the shape of "measured" drawdowns well for the Avon Park test. This likely resulted from "measured" drawdowns of less than 0.7 ft that were estimated poorly.

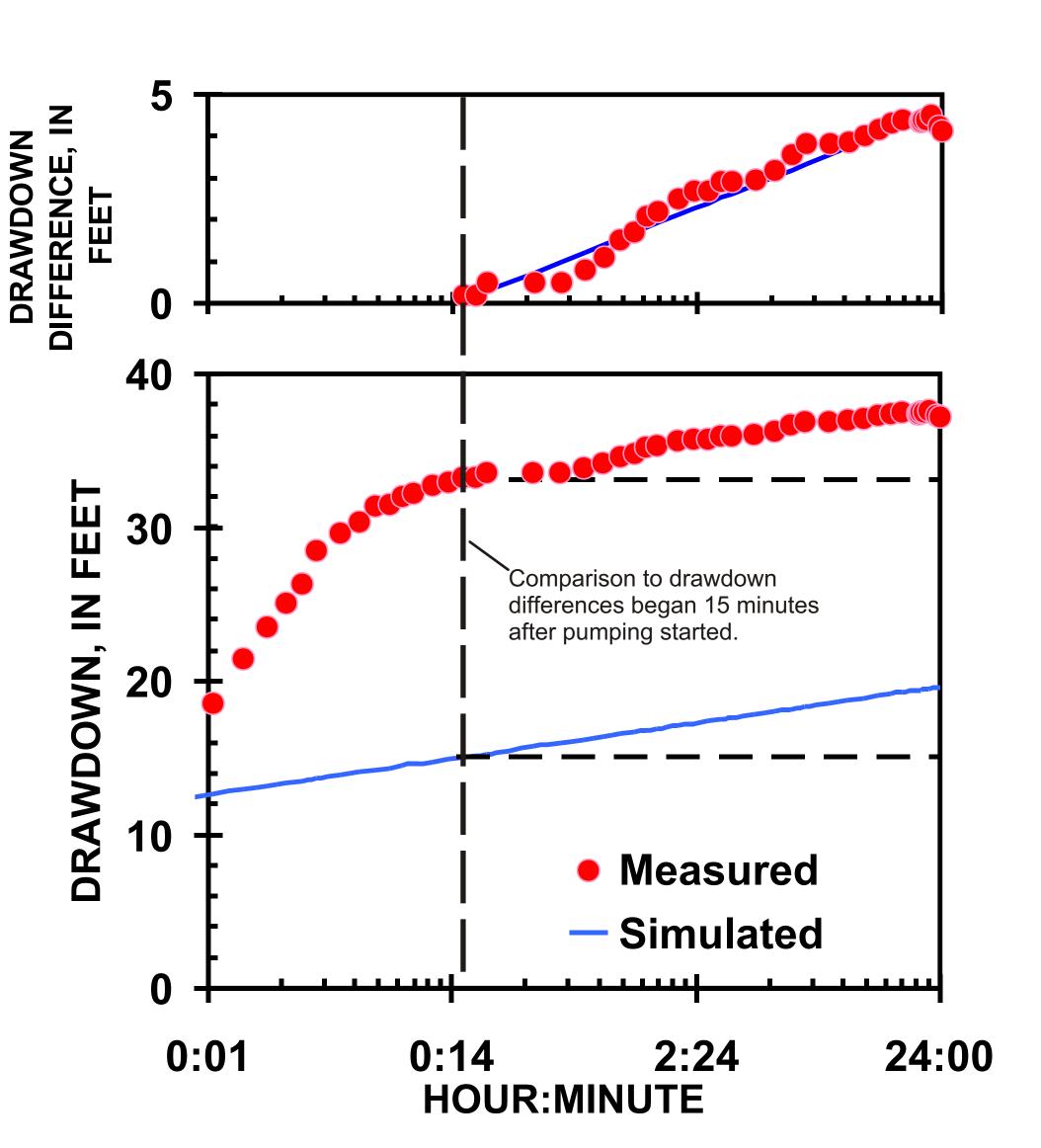
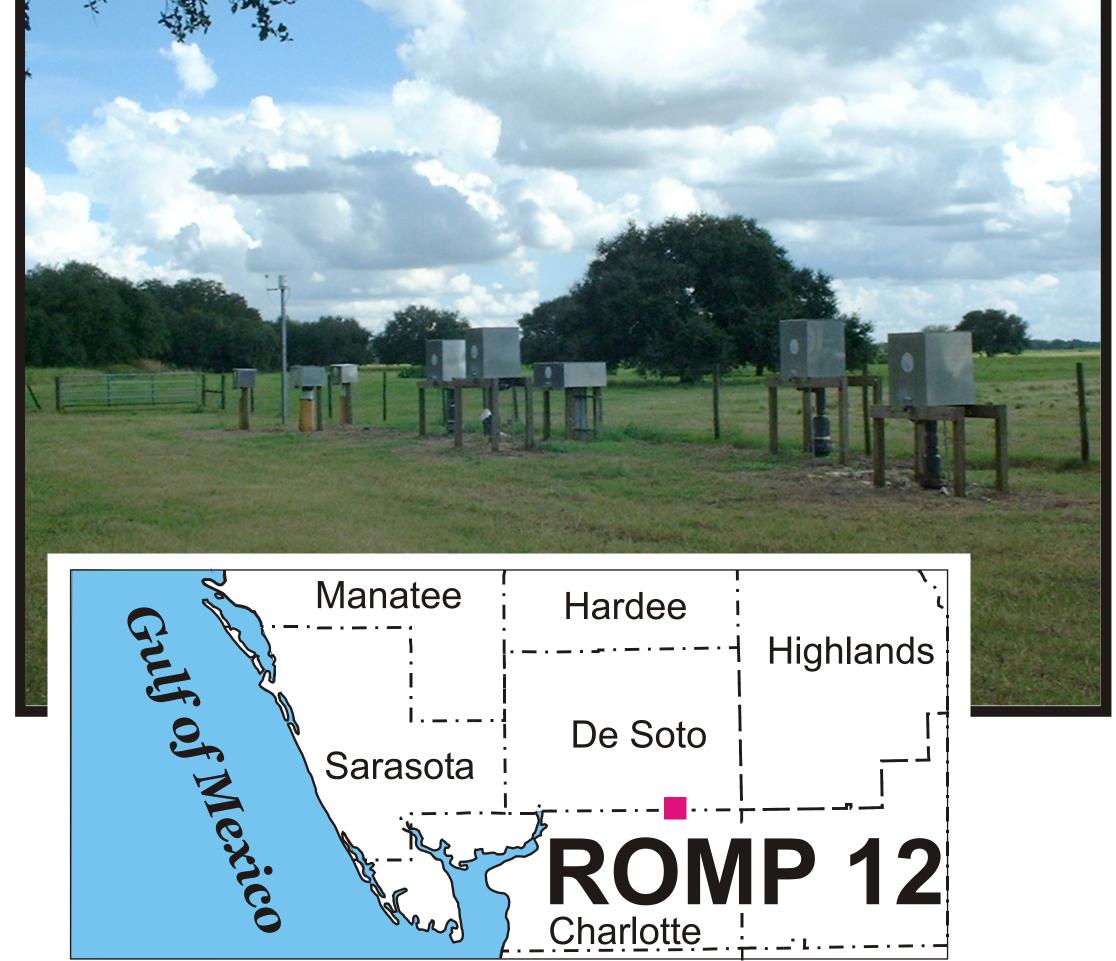


Figure 6.- Entry losses cause measured drawdowns to be greater than simulated drawdowns which can be negated by comparing drawdown differences.



Hydraulic conductivity and specific storage were estimated for six aquifers and five Location and well configuration of ROMP 12 site in southwest Florida.

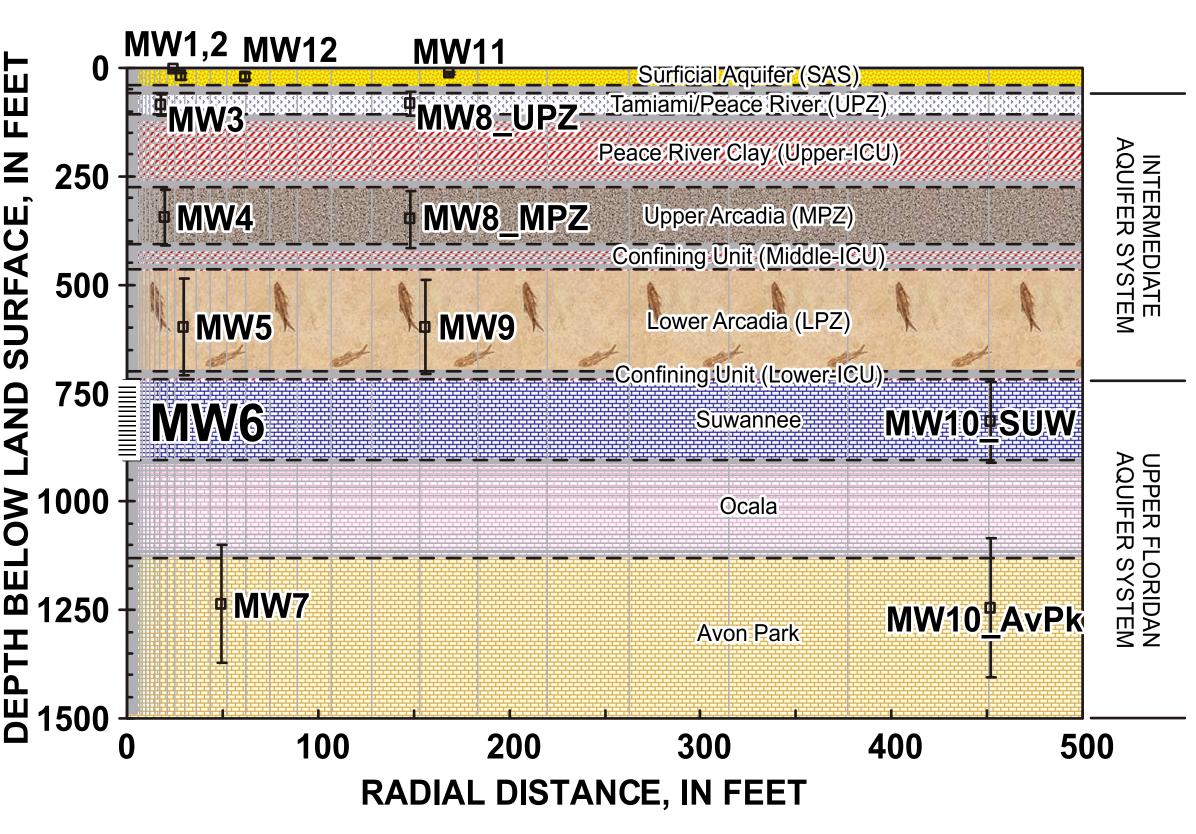
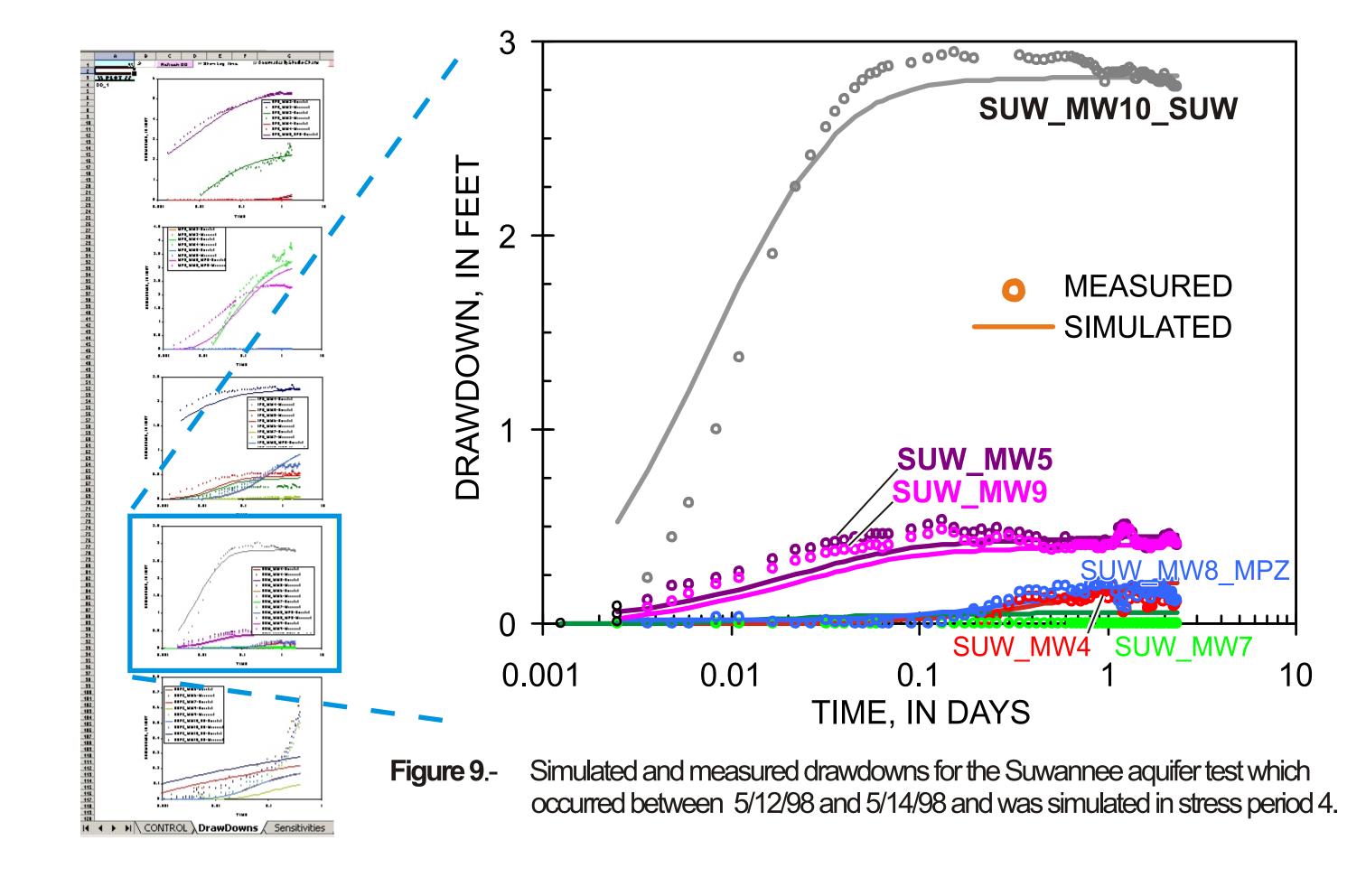


Figure 8.- Geohydrologic column at the ROMP 12 site, radial distances between observation wells and production well MW6, and MODFLOW grid.



Hydraulic Property Estimates

Lateral hydraulic conductivities of the aquifers that were estimated with Cooper-Jacob, Leaky Aguifer, or MODOPTIM differed less than an order of magnitude (Table 3), MODOPTIM estimates typically were between estimates from Cooper-Jacob and Leaky Aguifer solutions Hydraulic conductivity of Avon Park that was estimated with MODOPTIM exceeded the analytical estimates. The MODOPTIM estimate is likely better than the analytical estimates because information from the LPZ and Suwannee tests also affected hydraulic conductivity and specific storage of the Avon Park in the geohydrologic column.

Vertical hydraulic conductivities of the confining units were estimated consistently less with MODOPTIM than the Leaky Aguifer solution (Table 4). MODOPTIM estimates ranged from 3 to 10 times less than the Leaky Aguifer solution estimates of vertical hydraulic conductivities. The MODOPTIM estimates appeared more reasonable because related specific storage estimates deviated less from expected values of 10⁻⁶ to 10⁻⁵ ft⁻¹.

CONCLUSIONS

An approach has been presented for consistently estimating the hydraulic properties of a geohydrologic column with multiple aguifer tests. The geohydrologic column approach benefits from rigorous methods of interpreting from water level measurements. Combined results from Cooper-Jacob and Leaky aguifer solutions provide good initial estimates of lateral and vertical hydraulic conductivities for a radial. MODFLOW model. The many hydraulic properties that define a geohydrologic column are estimated with MODOPTIN which minimizes a weighted, sum-of-squares objective function. Hydraulic conductivity and specific storage estimates for all of aquifers and confining units will be consistent and reasonable because results from multiple aguifer tests are analyzed as a whole. These results are directly comparable to properties in a regional ground-water flow model, which makes the results much more useful than scattered analyses from multiple analytical solutions.

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Table 3.- Lateral hydraulic conductivity and specific storage estimates for the aquifers at ROMP 12.

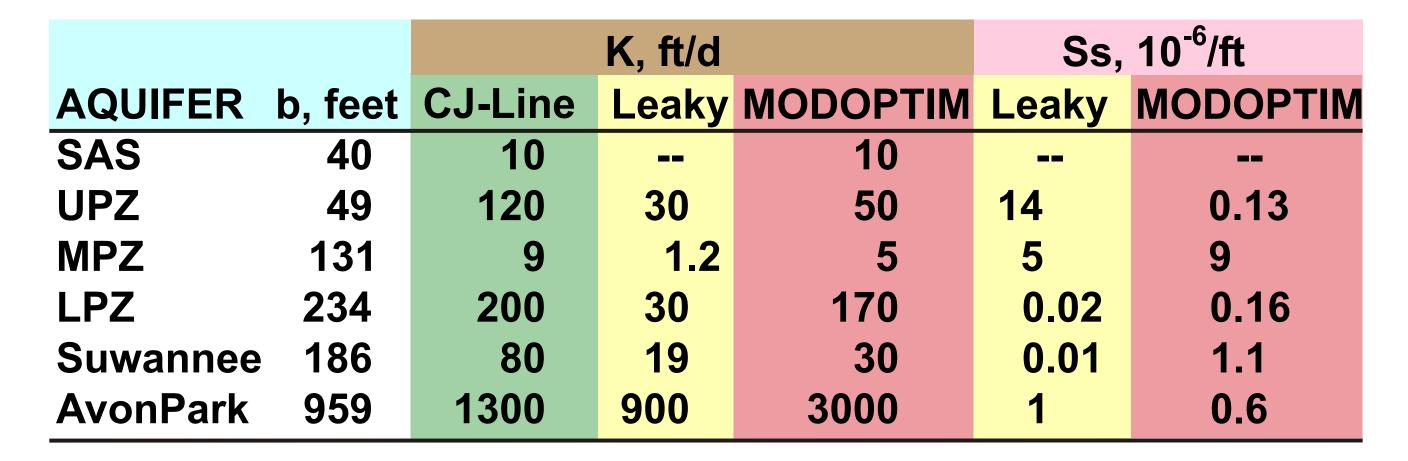


Table 4.- Vertical hydraulic conductivity and specific storage estimates for the confining units at ROMP 12.

		K ',	, π/d	Ss',	10 ³ /π
CONFINING UNIT	b, feet	Leaky	MODOPTIM	Leaky	MODOPTIM
UpperUpper-ICU	17	0.2	0.06	0.4	14
Upper-ICU	169	0.7	0.09	0.5	14
Middle-ICU	59	0.6	0.12	3000	3
Lower-ICU	20	0.3	0.12	200	2
Ocala-UFA	226	20	2	200000	1.3